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Influence of Axle Group Spacing on Pavement Damage

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Influence of Axle Group Spacing on Pavement Damage

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Abstract:	Current pavement design guides do not consider the effects of axle spacings. However, in many jurisdictions, higher loads on dual and triple axles are allowed for higher axle spacings. This practice is examined from a pavement viewpoint to ensure that dual or triple axles do not cause disporportionately greater damage than single axles. Damage effects of dual and triple axles on flexible pavements were evaluated as a function of axle spacing. The evaluation was based both on measured and calculated pavement responses to axle loads. Load Equivalency Factors are significntly influenced by pavement response parameters and by summation methods used for their derivation. The results display significant influence of the axle spacing on pavement damage. This indication should be taken into account when determining legal load limits on the axles. The AASHTO Guide appears to underestimate the damaging effect of dual and triple axles in comparison with single axles.
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INTRODUCTION

The extent to which structural pavement damage is caused by heavy vehicles, depends on several loading characteristics including axle loads, axle group configuration and spacing, load contact pressure, dynamic loading effects, and on their interactions. This paper addresses the effect of one of these load characteristics - axle group configuration and spacing. Based on a recent literature survey, the effect of axle spacing on pavement damage has not been systematically examined before.

Many jurisdictions, for example the Province of Ontario, regulate permissible axle group weights according to axle group spacing, while others, such as France and Sweden, do not [1]. In Ontario, the Highway Traffic Act [2] prescribes the permissible load limit for a dual axle (also known as tandem) and a triple axle (also known as tridem) which varies according to axle spacing. Axle spacing is defined as the distance between the two individual axles in a dual axle, and between the first and the third axles in a triple axle. The variation in permissible loads with the axle spacing has traditionally been based on the load carrying capacity of the bridge components. The permissible load on a single axle, however, is based on pavement considerations.

The AASHTO Pavement Design Guide [3] distinguishes between the damaging effects of dual and triple axle combinations, but assumes that these combinations have the same damaging effects regardless of the axle spacing within the combination. Considering flexible pavements, a tandem axle carrying 8 160 kg (18 000 lb, or, technically, 80 kN) on each axle has the AASHTO load equivalency factor of 1.38 regardless of the actual spacing between the two axles. However, if the spacing between the axles exceeds an unspecified distance so that the two axles can be considered to be independent, the corresponding AASHTO load equivalency factor is 2.00.

In 1988, a random survey of 2089 trucks was conducted at 16 Ontario locations. The data shows that the truck axle spacing ranges from about 1.0 m to 10.0 m (3.2 feet to 32 feet) and that its frequency distribution depends on truck

type. An example of the survey data for two truck types, trucks with 4 axles or less and trucks with 7 axles or more, is given in Figure 1. Because of data limitations, the frequency distribution of axle spacing in Figure 1 is plotted regardless of axle group type. Thus, a 2 m axle spacing may refer to a dual axle spacing, a two axle group spacing with no automatic load equilization, or the distance between two consecutive axles in a three or four axle group.

The distribution in Figure 1 appears to be bi-modal with a dividing line at about 2.0 to 2.5 m. According to the Ontario Highway Traffic Act [2], consecutive axles which are not articulated from a common attachment, or which are not designed to automatically equalize the load between the axles, are considered to be single axles if their spacing exceeds (a) 2.5 m in the case of 3 or 4 consecutive axles or, (b) 2.0 m in the case of two consecutive axles. Because the maximum allowable weight for a single axle (with dual tires) is always larger than that for an individual axle which is a part of an axle group, the axle group spacing in the range of 2.0 to 2.5 m is avoided.

The objectives of this study were 1) to evaluate the influence of axle spacing on damage caused to flexible pavements, and, 2) to determine maximum weights on dual and triple axles which would cause the same damage, axle per axle, as that caused by a single axle with the maximum legal load. The original motivation for this study was the need to develop a procedure for quantifying the damaging effect of various heavy load configurations using the measured pavement responses (surface deflections and asphalt concrete strains) obtained on our experimental testing facility [4].

The study is based on measured pavement response data obtained during the course of an RTAC study [5,6] and on calculated pavement responses using the elastic layer theory. In both cases, data were obtained for a large variety of axle loads and configurations.

QUANTIFICATION OF DAMAGING EFFECTS FOR DIFFERENT AXLE LOADS

The effect of heavy loads on pavement structural damage, such as fatigue (alligator) cracking and rutting, has been traditionally expressed using the

concept of load equivalency factors (*LEF*'s). For convenience, the *LEF*'s have been related to a standard axle load of 8 160 kg (18 000 lb) carried by a 8 160 single axle with dual tires. This load is called an Equivalent Single Axle Load (*ESAL*). Load equivalency factors can be obtained in two basic ways: by a field experiment or by an analytical evaluation of pavement responses to individual loads. The later way was used in this study.

LEF's Obtained by Field Experiments

A number of axle loads of a given magnitude and type required to cause a certain level of pavement deterioration, N_i, are determined in the field, and are compared to the number of *ESAL*'s required to cause the same amount of pavement deterioration on the identical pavement structure, N_{ESAL}:

$$LEF = \frac{N_{ESAL}}{N_i} \qquad (1)$$

The resulting *LEF*'s depend on the definition of pavement deterioration and its level, and on the type and strength of the pavement structure. Thus, for the same N_i, there may be different *LEF*'s for different pavement types, thicknesses, subgrades, and pavement distresses. The best known example of a field experiment is the AASHO Road Test of the early 1960s [7]. The Test encompassed a number of different pavement structures, but on a uniform subgrade. The *LEF*'s were mainly related to pavement damage in terms of roughness, which is directly related to the way the pavement serves the travelling public. This approach to obtaining load equivalency factors is extremely expensive and time consuming.

LEF's Obtained by Analytical Evaluation of Pavement Responses to Individual Loads

Measured or calculated pavement responses to individual load configurations are used to calculate load equivalency factors by assuming the following general relationship:

$$LEF_r = \left(\frac{R_i}{R_{ESAL}} \right)^n \qquad (2)$$

where:

LEF_r = Load Equivalency Factor based on pavement response r

R_i = pavement response r to the load of a defined magnitude and type designated as i

R_{ESAL} = pavement response r to one *ESAL*

n = exponent to ensure that *LEF* (from Equation 1) is equal to LEF_r (from Equation 2) for pavement response r.

This approach, used in this study, requires the identification of pavement responses, such as strains and stresses, which cause specific pavement structural distresses. These distresses should be related to pavement deterioration which affects the way pavements serve the travelling public. As a corollary, it is assumed that increased strains and stresses in the pavement structure increase pavement distresses (and reduce the pavement serviceability). Furthermore, this approach is faced with two main complications. Firstly, load equivalency factors depend on the type and severity of pavement distresses, of which there are many possible combinations. Secondly, according to Equation 2, it is assumed that the pavement response to an axle group load, which can be rather complex, can be characterized and summarized by one number. However, in the absence of a universally accepted computational procedure to summarize pavement responses in terms of one encompassing number, the use of different computational procedures may yield different results.

Response Parameters Used

The load equivalency factors used by an agency should be based on the pavement distress or distresses which trigger the local need for pavement rehabilitation. For example, Hallin et al [8] developed LEF's for Washington state based on fatigue cracking because "cracking is the principal form of asphalt pavement distress in Washington state". A statistical examination of Ontario pavement distress data [9] reveals that practically all 15 routinely evaluated pavement surface distresses occur at the critical levels of severity

and density requiring rehabilitation, and that fatigue cracking is not a predominant distress. The 15 distresses include ravelling, flushing, rutting, distortion, and different types of cracking such as pavement edge, transverse, and alligator. For this reason, the following three basic pavement responses, linked previously to the formation of pavement distress, have been used in this study:

a) *Pavement surface deflection:* This response has been linked to pavement deterioration, measured mainly in terms of roughness. Several pavement distresses, such as cracking, distortion, and rutting, can contribute to pavement roughness.

b) *Interfacial strain:* Strain at the bottom of the asphalt concrete layer which has been related to fatigue (alligator) cracking.

c) *Vertical strain on the top of the subgrade:* This response has been related both to rutting in the pavement structure and to pavement deterioration.

A typical history of these three responses for a flexible pavement subjected to a moving dual axle load is shown in Figure 2.

Summation of Pavement Responses to Axle Loads

The comparison of damage caused by different loads requires quantification and summation of pavement response curves (Figure 2) resulting from the passage of these loads. Two approaches can be used: discrete summation methods or integration methods. Discrete methods use only discrete values at the peaks and valleys of the response curve, while integration methods attempt to use the whole response curve. The two summation methods are illustrated in Figure 3 using pavement response curves obtained for single and dual axles. Also shown in Figure 3 are three different dual axle response curves (Case a, b, and c) which will be discussed later.

Discrete Methods

Three discrete methods used in this study, RTAC, University of Waterloo, and Peak, are schematically shown in Figure 4. *LEF*'s were calculated by summing peak to valley responses using a modified Equation (2) as follows:

$$LEF_{r,m} = \frac{\sum_{i=1}^{p} (r_i)^n}{(R_{ESAL})^n} \qquad (3)$$

where:

$LEF_{r,m}$ = Load Equivalency Factor for pavement response r, and method m.

r_i = Discrete pavement response for load cycle i identified by method m.

n = As defined before, adopted to be 3.8. This value was also used in the RTAC study [5,6] (both for surface deflections and interfacial strains) and is based on an extensive review by Christison [6].

p = Number of load cycles (axles).

The exponent n can vary for different pavement response parameters and depends on the procedures used to obtain it. For example, it is well recognized that n derived from laboratory fatigue tests of asphalt concrete mixes depends on the mix composition, the testing conditions, and the definition of failure [10].

RTAC Method

This method was originally used for the analysis of measured pavement responses as part of the Canadian Vehicle Weights and Dimensions Study [5,6]. For surface deflections (and in this study also for strains on the top of the subgrade), the peak under the lead (first) axle was extracted first, followed by the trough to peak differences in the response curve for the subsequent axles (Figure 4). For interfacial strains, only the peak tensile strains measured from the rest (zero) position were used.

University of Waterloo Method

This method was developed by Hutchinson et al [11] for isolating and counting pavement surface deflection cycles. In this study, it was also used for the summation of subgrade strains. The method follows an ASTM Standard Practice [12] which recommends that the highest peak and lowest valley be used first, followed by the second largest cycle, etc., until all peak counts are used (Figure 4).

Peak Method

For surface deflections and subgrade strains, the Peak method uses the total response under each axle from the rest position. For interfacial strains, the Peak method uses the peak to trough rise and falls in the strain history (Figure 4), a procedure which is identical to that recommended by ASTM Standard Practice for Cycle Counting in Fatigue Analysis [12] and, for this reason, the Peak method appears to be an improvement over the RTAC method.

Regarding surface deflections, proponents of this method [13] argue that even though the surface deflections between two subsequent axles do not reach a rest position, the asphalt concrete layer at this location reverses its curvature (tensile strain to compressive strain, Figure 2) so that the inclusion of the total deflection best models the overall pavement response.

Another argument in support of this method may be advanced by considering how different response curves, such as those shown for Cases a and b in Figure 3, are accounted for by the Peak method. In Case a, the peak axle responses D_1 and D_2^* are nearly equal, while in Case b the two peaks differ considerably (D_1 versus D_2^{**}). Case c has the same peaks as Case a, but the duration of the load is longer. All three cases have the same trough D_2. The Peak method uses responses D_1 and D_2^* *(or D_2^{**} for Case b)* and thus distinguishes between the damaging effects of the two Cases a and b while the other two methods, RTAC and Waterloo, do not (they are based on responses D_1 and D_2).

Integration Methods

Flexible pavements respond to loads as visco-elastic systems with resulting permanent and elastic strains. The permanent strains are influenced by both the amount and the duration of load. Integration methods take both spatial and temporal variability of the load into account by integrating the response curve expressed as a function of time or distance. Referring to Figure 3, integration methods distinguish between the response curves of not only Cases a and b, but also between Cases a and c, which have similar peaks but different load duration. The formula developed in this study for calculating *LEF*'s by integration is shown in Figure 3, Eq. 5. Conceptually, it resembles the formulation used by Govind and Walton [14]. The exponent n for this method was also set at 3.8 to enable a direct comparison with discrete methods. There is no precedent in the literature for the value of n.

The integration methods include influence of the rate of loading on pavement damage and eliminate ambiguity in defining the peaks and valleys required for discrete methods. However, the validity of integration methods has not been proven.

MEASURED AND CALCULATED PAVEMENT RESPONSES

Measured Pavement Responses

Measured pavement responses used in this study were taken from the Canadian Vehicle Weights and Dimensions Study [5]. This 1985 study provides a large set of measured pavement responses in terms of surface deflections and interfacial strains obtained at 14 sites for a variety of loading conditions. The results based on these measurements are referred to in this study as "RTAC measurements".

Calculated Pavement Responses

Computational Method

The flexible pavement was modeled as an idealized elastic layered system and its responses to loads were calculated by the ELSYM5 computer program [15]. The use of the elastic layer theory to obtain load equivalency factors has been successfully used before [8,16,17].

Pavement Structure

Calculations were done for the thin and thick flexible pavement structures shown in Figure 5. The thin section has a structural number (*SN*) of 3.0, and represents a low-volume road; the thick section has a *SN* of 5.7 and represents a typical structure for a high-volume facility. It may be noted that the average *SN* for the 14 sections used in the RTAC study was 5.0.

Pavement Loadings

Analyses were done for single, dual, and triple axle groups. All axles had dual tires spaced about 350 mm (14 in.) apart. The tire footprints were assumed to be circular with a pressure of 690 kPa (100 psi). Axle loads on individual axles ranged from 5 450 kg (12 000 lb) to 11 800 kg (26 000 lb). As the load increased, the tire contact area increased because the tire pressure was held constant. A similar loading arrangement was used by Kilareski [17].

Location of Maximum Deflections and Strains

When comparing pavement response to different axle loads, it is important to use the maximum responses in all cases as a common denominator. Analysis shows that the maximum responses for deflection and strains occur on the line at the midpoint between the dual tires, regardless of axle spacing. The responses along this line were calculated to identify all relevant features of the response curve required for analysis.

RESULTS

Effect of Axle Spacing on Pavement Damage

Load equivalency factors are plotted as a function of axle spacing for double and triple axles in Figures 6 and 7, respectively. For easier comparisons, the axle loading in Figures 6 and 7 is kept constant at a standard design load of 8 150 kg (18 000 lb) per individual axle. The results are briefly interpreted in the following.

Summation of Pavement Responses to Axle Loads

Summation methods (methods used to quantify and summarize pavement response curves) have a large influence on *LEF's*, notably on *LEF's* based on surface deflections and subgrade strains. In general, the Peak method yields the highest LEF's, followed by the Waterloo method and finally by the RTAC method. The LEF's obtained by the Integration Method are shown only for dual axle and surfaces deflections. While the Integration method appears to be conceptually sound, the selection of the exponent n in Eq. 5 (figure 3) is rather arbitrary. Based on the available information and data, it is not possible to unequivocally recommend any particular summation method, however, the peak method appears to be the best candidate. As will be shown later, the summation methods have a decisive influence on the LEF's.

Measured Versus Calculated Pavement Responses

It appears that the summation methods have a larger influence on the resulting *LEF's* than on whether the original pavement responses (on which the methods operate) were measured or calculated. For example, considering *LEF's* for dual axles based on surface deflections (top of Figure 6), the results can be grouped according to the summation method used rather than to whether the pavement responses were measured or calculated. Regarding the quantification of pavement damage caused by various load configurations, future efforts should be directed toward a better understanding of the influence of different pavement response parameters and the summation methods. This appears to be a

much more fruitful endeavor than the fine tuning of procedures for measuring or calculating pavement responses to loads.

Pavement Response Parameters

Overall, regardless of the summation method used, *LEF*'s based on deflections are larger than those based on strains (interfacial, and subgrade) and decrease with increasing axle spacing. The *LEF*'s based on interfacial strains and calculated by the RTAC method increase (rather than decrease) with larger axle spacing. The same also roughly applies to subgrade strains processed by the RTAC method. This phenomenon can be explained by noting that when axles are close together, the compressive strain in asphalt concrete caused by one axle can offset a part of the tensile strain caused by an adjacent axle, effectively reducing the net tensile pavement strain. Because the RTAC method does not work with the total strain cycle (it excludes compressive strain from the *LEF*'s calculation), but still uses the reduced tensile strain, the RTAC LEF's for interfacial strains can decrease with axle spacing.

Axle Spacing

For thick pavements, axle spacing has a significant influence on *LEF*'s, particularly for those determined for surface deflections and vertical strains using the Peak method. As expected, for large axle spacings, all *LEF*'s (for 8 160 kg loads) tend to approach 2.0 for dual axles and 3.0 for triple axles, regardless of response parameters or summation method used.

Pavement Structure

The influence of axle spacing on *LEF*'s decreases with pavement structural strength. Thin, structurally weak pavements do not distribute axle loads effectively. Consequently, their responses are governed mainly by individual axles and not by the whole axle group. For example, regardless of axle spacing or the summation method used, *LEF*'s for dual axles based on interfacial strains are equal to 2.0.

Comparison With AASHTO Factors

Typical *LEF*'s recommended by the AASHTO Guide [3] for dual and triple axles are given in Table 1. The AASHTO *LEF*'s do not change with axle group spacing. Also shown in Table 1 are *LEF*'s for zero spacing and for spacing large enough so that axles can be considered to act independently. This spacing is not defined by the AASHTO Guide. For example, a triple axle with the weight of 8 160 kg (18000 lb) on each of its three axles has an LEF of 1.66 regardless of axle spacing. When the spacing between the three axles exceeds an unspecified distance, the LEF jumps to 3.0. If, at the other extreme, all three axles were concentrated in one position, the LEF exceeds 53. Considering that the spacing between the consecutive axles can be quite variable (Figure 1), particularly for axle groups which do not equalize loadings, the results suggest that the AASHTO *LEF*'s would benefit from including the influence of axle spacing.

Damage Comparisons

The maximum allowable axle weight for single axles with dual tires in Ontario is 10 000 kg (22 046 lb). This axle weight represents 2.0 to 2.1 *LEF*'s, depending on the pavement response and pavement structure. The value of 2.0 or 2.1 does not depend on the (discrete) summation methods used because the single axles have only one peak value and the LEF can be calculated directly from Eq. 2. It may be also noted that the corresponding AASHTO LEF is 2.18 [3] (for p_t = 2.5, and SN = 5.0).

If the single axle can be allowed to have a maximum of 2.0 *LEF*'s, then, based on the principle that any axle can cause identical damage, a dual axle can be allowed to have 4.0 *LEF*'s and a triple axle can be allowed to have 6.0 *LEF*'s. Based on this principle, what are the maximum weights for dual and triple axles causing the same pavement damage as the single axle weighing 10 000 kg? How do these weights compare with legislative limits? These questions are addressed in this section.

Figures 8 and 9 show the influence of axle spacing and axle group weights on *LEF*'s for dual and triple axles. The results are shown only for the thick pavement which is more representative. Figures 8 and 9 are derived from calculations similar to those used for Figures 6 and 7, respectively. Also shown in the two figures are horizontal lines indicating *LEF*'s (damage levels) for a corresponding number of single axles. For example, considering the results obtained for dual axle and surface deflections (top of Figure 8), based on the Peak method and 1.0 m axle spacing, the total dual axle group weight, having the same *LEF* (causing the same damage) as two single axles with the maximum allowable weight (i.e. 4.20), is about 14 900 kg.

The results of Figures 8 and 9 are summarized in Table 2 together with the AASHTO [3] data and the Ontario allowable limits [2]. The following two basic observations can be made, based on Table 2:

a) Ontario permissible weights for dual and triple axles are lower than those established by any computational scenario with the exception of the deflection-based Peak method. The greatest difference (3 400 kg) exists for triple axles with the largest spacing (4.8 m). Ontario regulations allow 28 600 kg, while the deflection-based Peak method would allow only 25 200 kg.

b) The AASHTO-based weights are higher than the weights based on deflections and interfacial strains regardless of the summation method used. They are roughly similar to the allowable weights based on a subgrade strain response, evaluated by the RTAC method. Overall, it appears that the AASHTO Guide may underestimate the damaging effects of dual and triple axles in comparison with single axles.

CONCLUSIONS AND RECOMMENDATIONS

1. Load Equivalency Factors are significantly influenced by a) pavement response parameters (deflection, strains) on which they are based and, (b) summation methods used for their calculation. There is a need for a better understanding of the influence of different pavement response parameters and summation methods on the quantification of pavement damage due to multiple axle loads.

2. Contrary to the inference based on pavement design guides, axle spacings have a significant effect on pavement damage which should be accounted for in determining the permissible load limits on dual and triple axle units.

3. Permissible weights on dual and triple axles in Ontario are generally lower than those determined by the various computational methods used to analyze pavement damage. The Peak method, however, gives up to 12 percent lower permissible weights for larger axle spacings compared to the Ontario legal limits.

4. It appears that within the practical range of axle spacings, pavement damage can be significantly reduced by increasing axle spacings.

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Table 1/ AASHTO Load Equivalency Factors for Tandem (Dual) and Triple Axles

Axle Type	**Zero Spacing** (only one axle)	**Typical Spacing**[1)]	**Large Spacing**[1)] (independent axles)
Tandem	13.9	1.38	2.0
Triple	above 53	1.66	3.0

Note 1: Spacing between consecutive axles. The actual spacing is not defined.

Conditions: Flexible pavement, SN = 5, p_t = 2.5.
Load on each individual axle is 8 160 kg (18 000 lb).

Source: Reference 2.

Table 2/ Equivalent Damage Loads for Dual and Triple Axles[1)]

The total weight of dual (or triple) axles in kg which causes the same amount of damage as 2 (or 3) single axles with a maximum allowable weight of 10 000 kg.

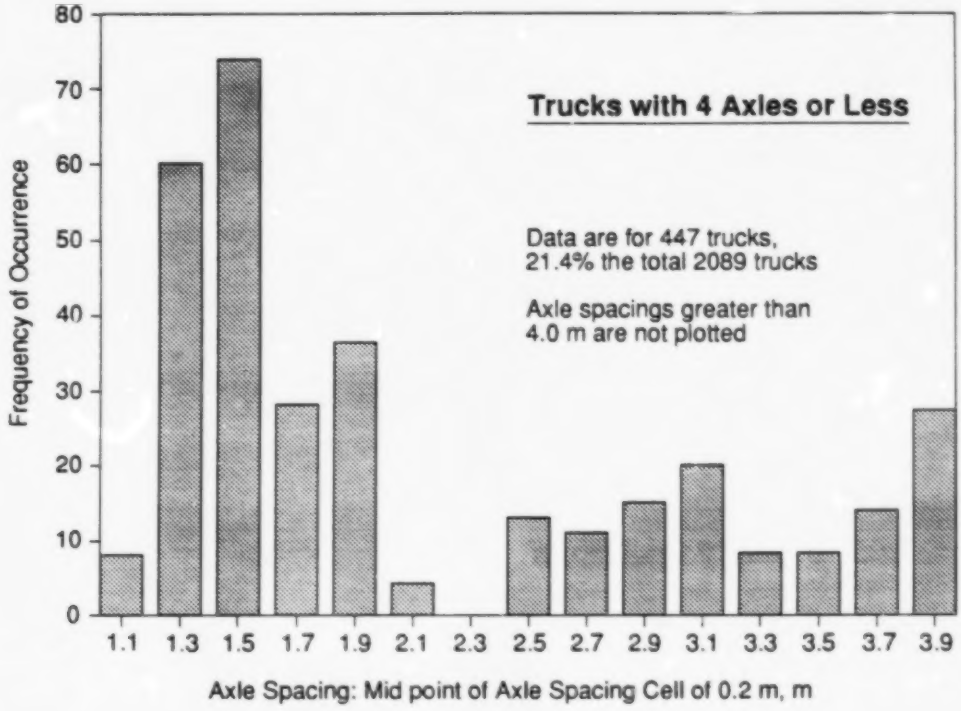
How Determined	Dual Axle Spacing		Triple Axle Spacing	
	1.0 m	1.8 m	2.0 m	4.8 m
Deflections				
Peak Method	14 900	16 700	20 300	25 200
Waterloo Method	18 000	19 600	26 200	28 300
Strains, A.C.				
Peak Method	18 300	18 900	28 300	29 900
RTAC Method	19 000	19 700	32 100	29 900
Strains, Subgrade				
Peak Method	17 100	18 600	26 100	30 100
RTAC Method	20 600	22 000	31 000	35 500
AASHTO[2)]	21 600	21 600	34 300	34 300
Ontario Weight Limits[3)]	15 400	19 100	19 500	28 600

Notes:

1) (Thick) flexible pavement, SN = 5.7, See Figure 5

2) Source: Reference 2, SN = 5.7, p_t = 2.5, LEF = 4.2 for dual axle or 6.3 for triple axle.

3) Source: Reference 16



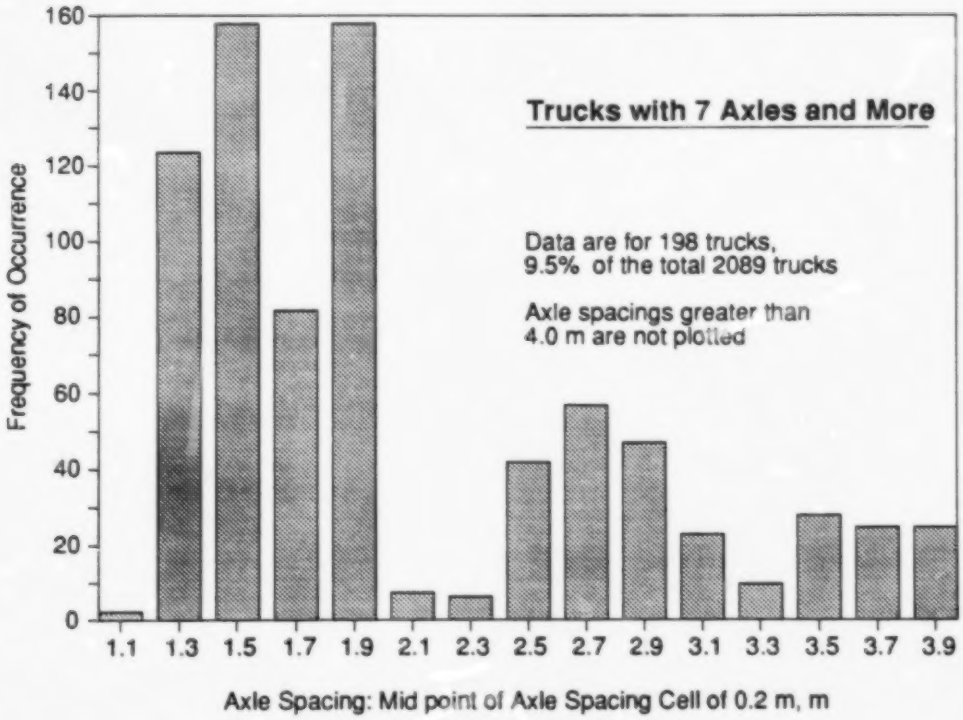


Figure 1/ Frequency Distribution of Axle Spacing for Two Truck Types

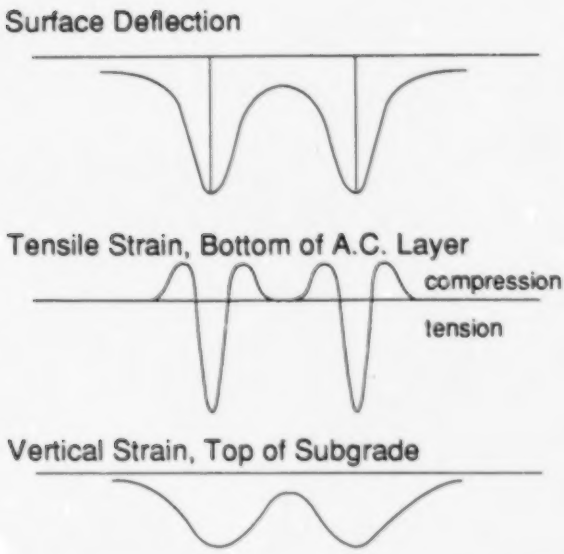
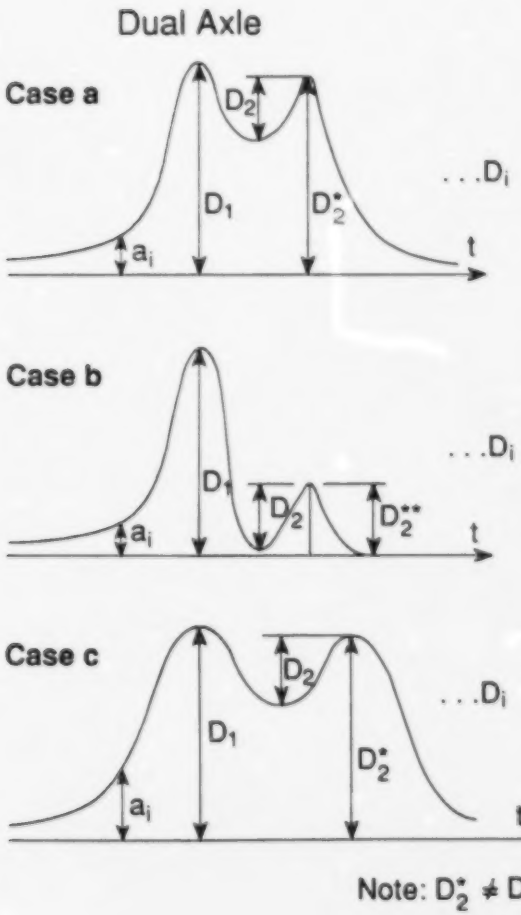


Figure 2/ Typical Response of a Flexible Pavement to a Moving Dual Axle Load



Calculation of Load Equivalency Factors

1. Discrete Methods

$$LEF = \Sigma \left(\frac{D_i}{D_s} \right)^n \qquad (4)$$

2. Integration Methods

$$LEF = \frac{\int_0^t | a_i^n | \, dt}{\int_0^t | a_s^n | \, dt} \qquad (5)$$

Figure 3/ Discrete and Integration Methods for Calculation of Load Equivalency Factors

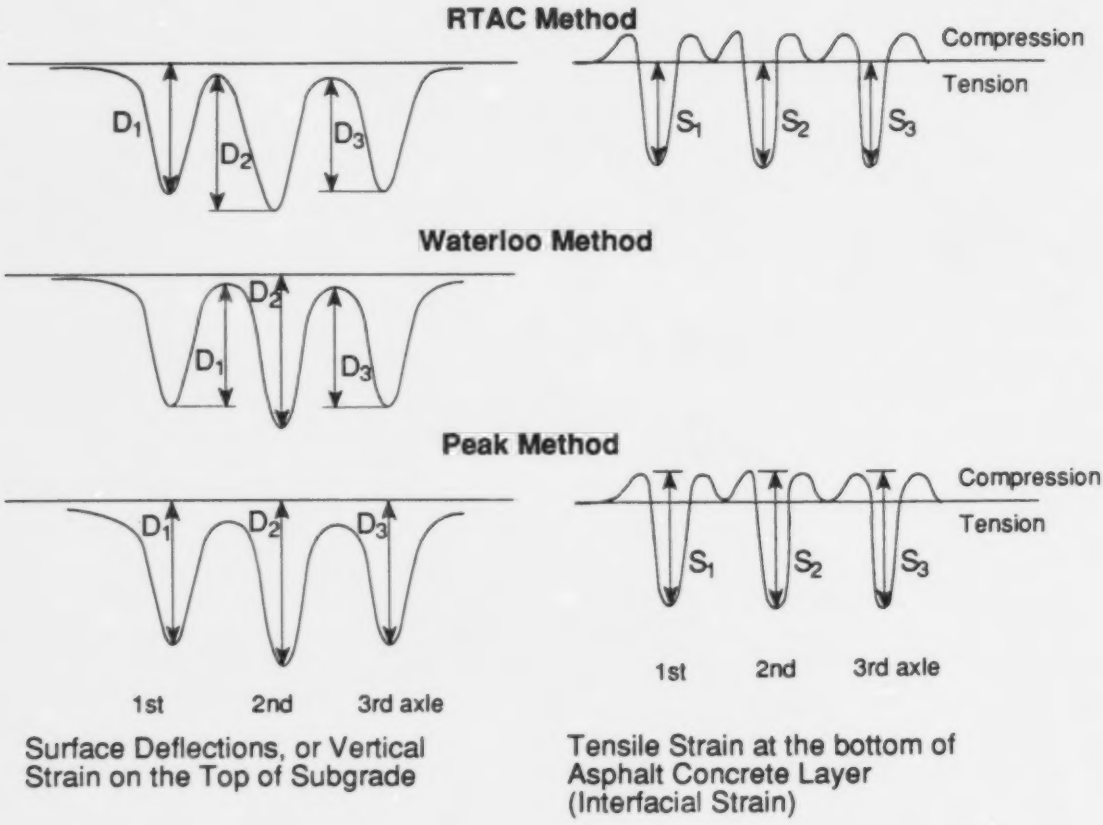


Figure 4/ Discrete Methods Used to Calculate the Effect of Multiple Axle Groups

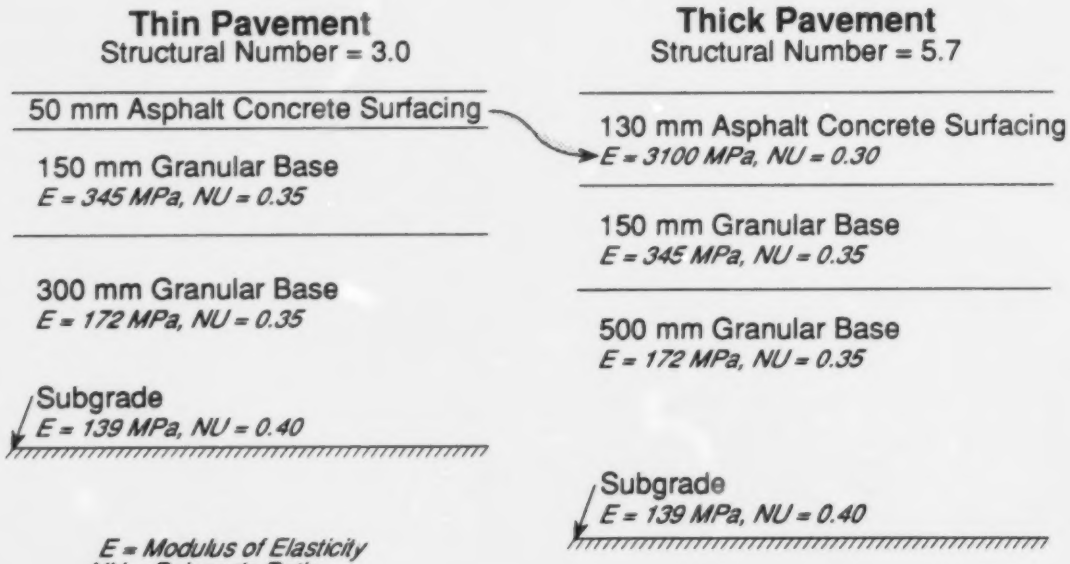

Thin Pavement
Structural Number = 3.0
50 mm Asphalt Concrete Surfacing
150 mm Granular Base
E = 345 MPa, NU = 0.35
300 mm Granular Base
E = 172 MPa, NU = 0.35
Subgrade
E = 139 MPa, NU = 0.40
E = Modulus of Elasticity
NU = Poisson's Ratio
Thick Pavement
Structural Number = 5.7
130 mm Asphalt Concrete Surfacing
E = 3100 MPa, NU = 0.30
150 mm Granular Base
E = 345 MPa, NU = 0.35
500 mm Granular Base
E = 172 MPa, NU = 0.35
Subgrade
E = 139 MPa, NU = 0.40

Figure 5/ Flexible Pavement Structures Used in Analysis

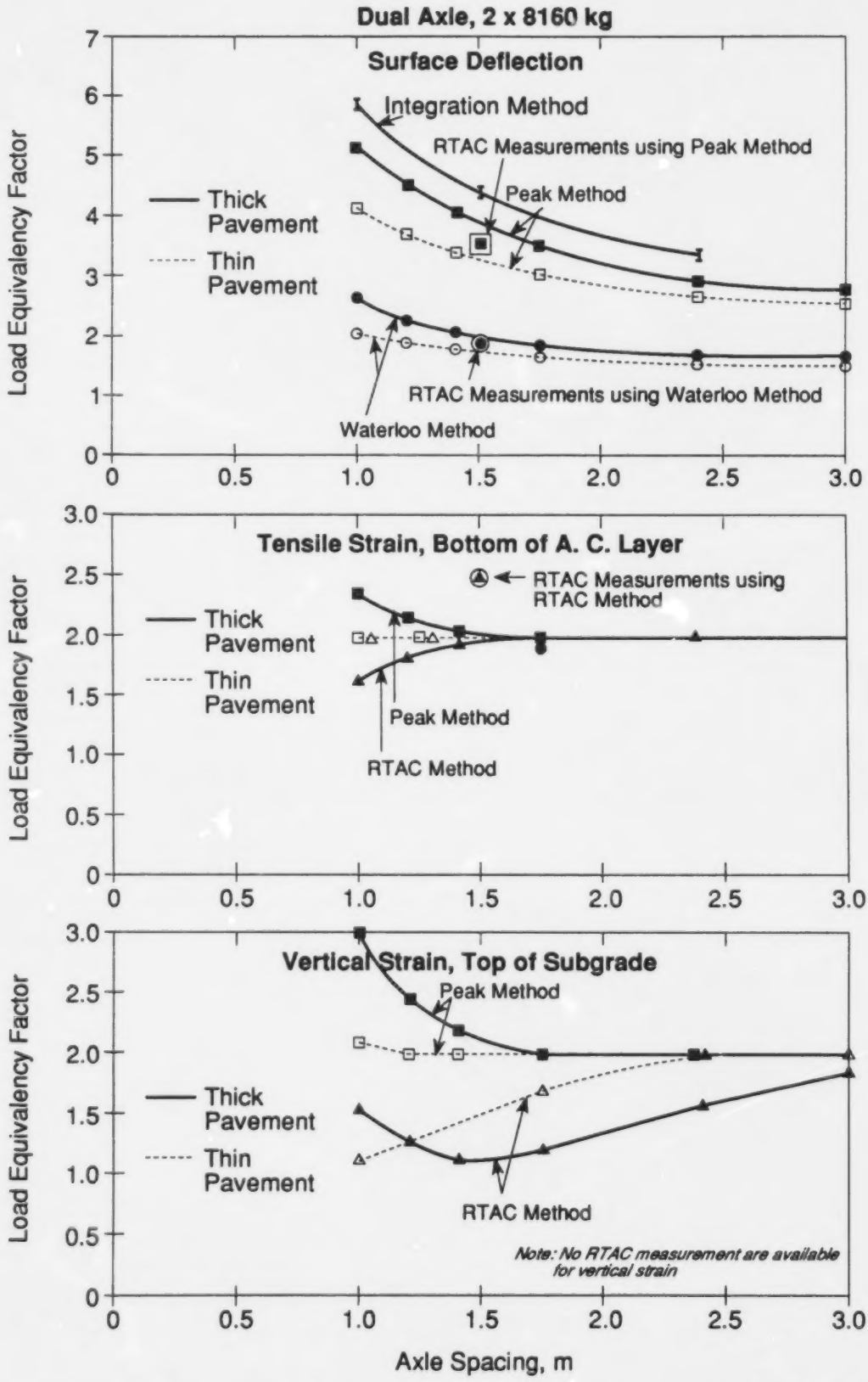


Figure 6/ Influence of Axle Spacing on Load Equivalency Factor for Dual Axles

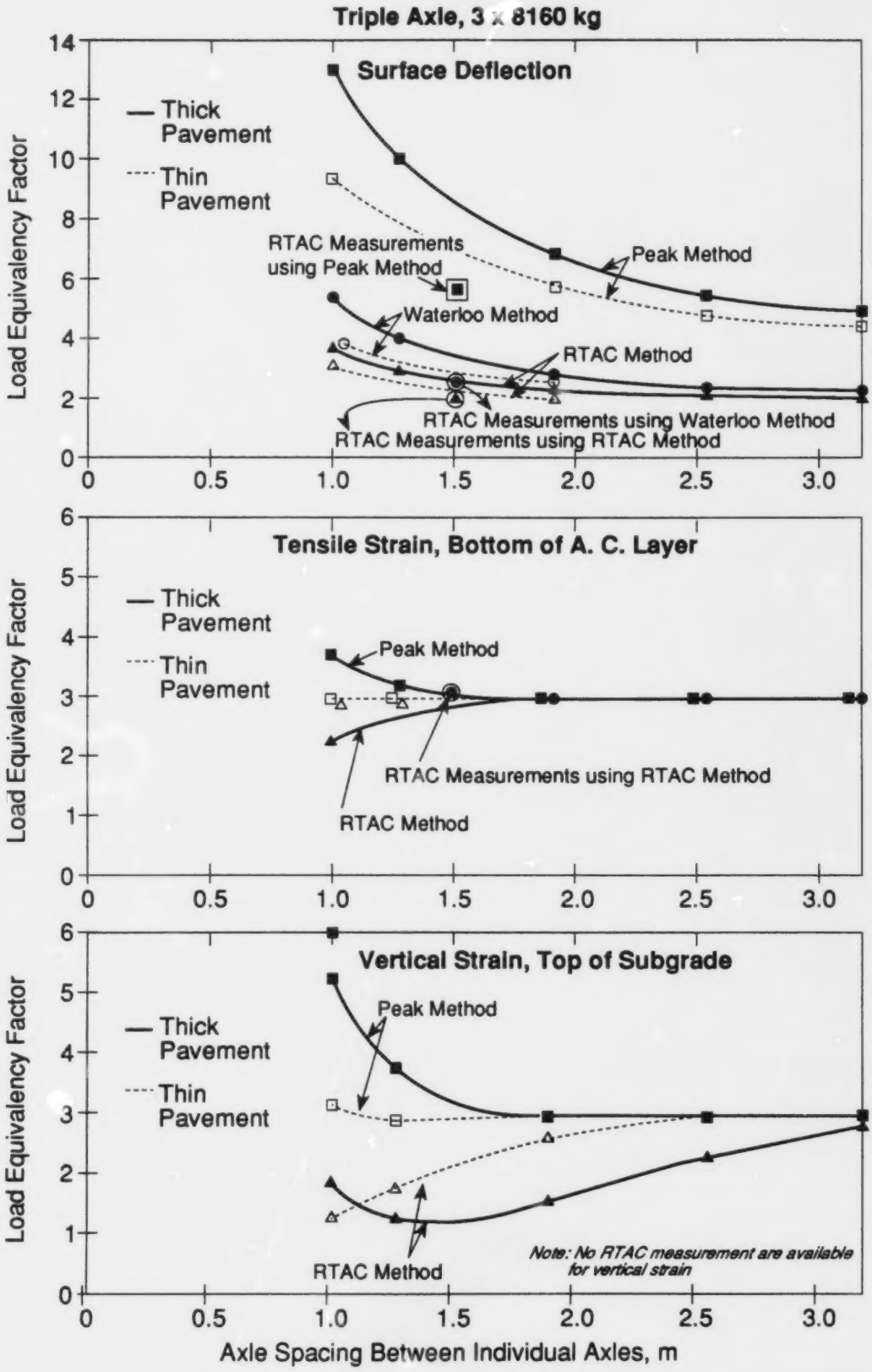


Figure 7/ Influence of Axle Spacing on Load Equivalency Factor for Triple Axles

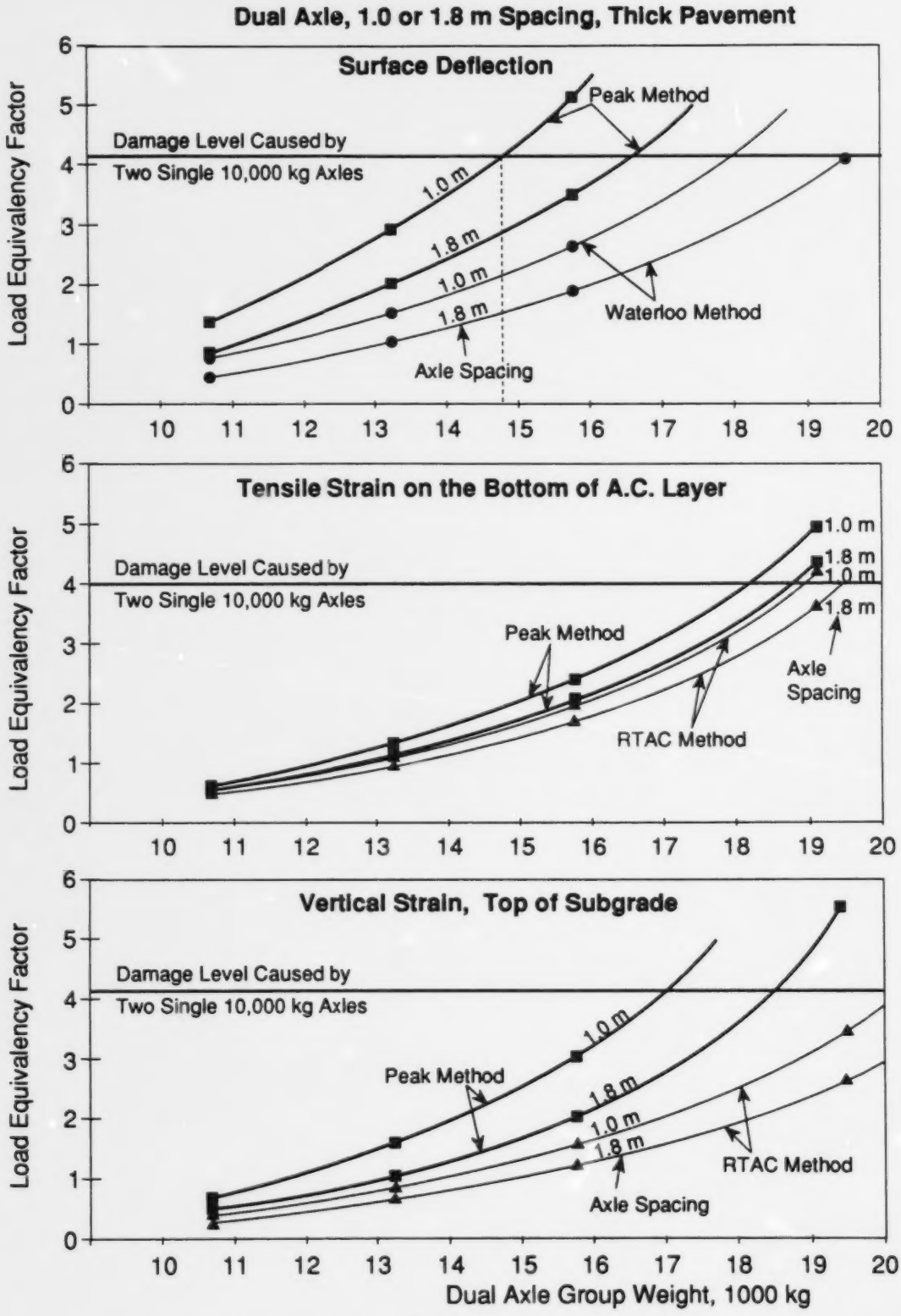


Figure 8/ Comparison of Damage Caused by Two Single Axles Versus One Double Axle Group (Thick Pavement)

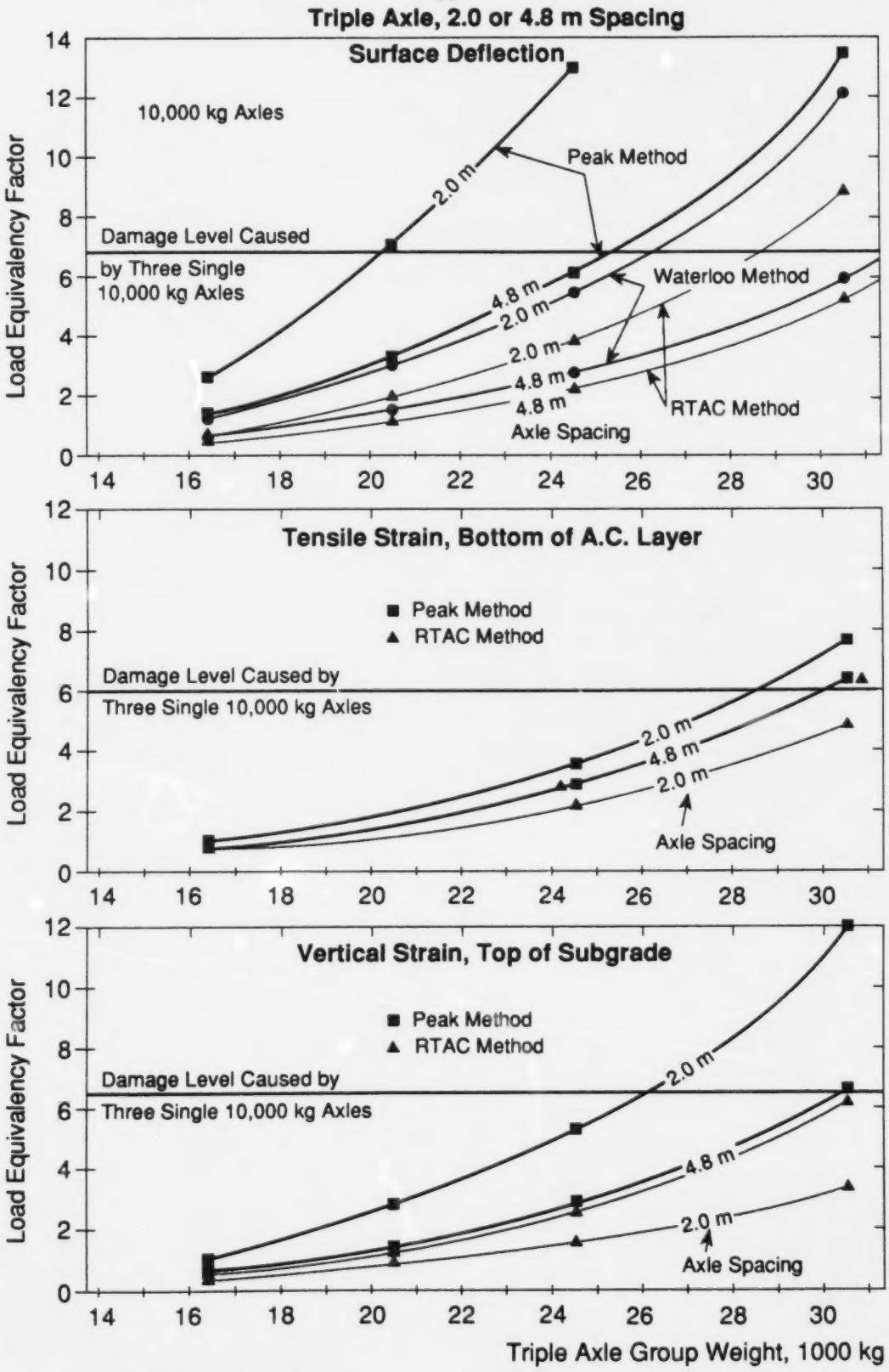


Figure 9/ Comparison of Damage Caused by Three Single Axles Versus One Triple Axle Group (Thick Pavement)